sw 9716

DAPNIA/SPhN-97-11

01/1997

**Pseudoscalar meson photoproduction at high energies :
from the Regge regime to the hard scattering regime**

M. Guidal, J.-M. Laget, M. Vanderhaeghen

DAPNIA

Submitted to Physics Letters B

Pseudoscalar meson photoproduction at high energies : from the Regge regime to the hard scattering regime.

M. Guidal, J.-M. Laget and M. Vanderhaeghen

CEA, DAPNIA/SPhN, CE Saclay, F91191 Gif-sur-Yvette Cedex, France

Abstract

A model for high energy pion photoproduction is presented which interpolates between the low and high momentum transfer regions. At low momentum transfer (which is described in terms of Regge trajectory exchanges), the model is able to give an economical description of the numerous high energy unpolarized and polarized $\gamma N \rightarrow \pi N$ data. At higher momentum transfer, a description based on saturating Regge trajectories and which satisfies quark counting rules at asymptotically large transfers, is found able to describe the few existing $\gamma p \rightarrow n\pi^+$ data. The model can be used as a guidance to interpret forthcoming data at large momentum transfers.
PACS : 13.60.Le, 12.40.Nn, 12.38.Bx

Hard exclusive reactions permit to select and study the simplest partonic component in the ground state wave function of a hadron. However, an electron energy in the range of 15-30 GeV like ELFE is needed [1]. In the meanwhile, with the presently existing high duty cycle electron facilities at lower energies ($E_\gamma \gtrsim 4$ GeV), e.g. with the large acceptance detector CLAS at TJ-NAF, the study of photoproduction reactions at large angle opens up a virgin, unexplored field. The present Letter addresses photoproduction reactions in this transition region between low momentum transfer (where a description in terms of hadronic degrees of freedom through effective hadronic Lagrangians is valid) and large momentum transfer (where the degrees of freedom are quarks and gluons within the domain of perturbative QCD (pQCD)). We will focus on the pseudoscalar meson photoproduction reactions on a nucleon and present a model covering the whole momentum transfer domain. At high energy and low momentum transfer, the large data set which exists for the pion photoproduction reactions allows to put severe tests on the theoretical model for $\gamma N \rightarrow \pi N$. Subsequently we discuss the extension of the model to larger momentum transfer.

At energies above $E_\gamma \gtrsim 4$ GeV, the main features of the experimental differential cross sections for pseudoscalar meson photoproduction reactions are a strongly collimated peak at forward ($|t| \lesssim 2$ GeV²) and backward ($|u| \lesssim 1$

GeV^2) angles, corresponding to the exchange of mesons in the t -channel and baryons in the u -channel respectively. Regge theory [2] [3] permits to give a simple and natural description of the smooth energy and angular dependence ($s^{2\alpha(t)-2}$) of these peaks, where s and t are the Mandelstam variables of the reaction and where $\alpha(t)$ is the exchanged trajectory.

The starting point for our model of pseudoscalar meson photoproduction is given by a Feynman diagram formalism as in Ref.[4], consisting of t - and u -channel exchanges. We have then replaced the usual pole-like Feynman propagator of a *single* particle (i.e. $\frac{1}{t-m^2}$ where m is the mass of the exchanged particle) by a Regge propagator which takes into account the exchange of a *family* of particles with the same internal quantum numbers. In the case of the pion photoproduction reaction, we aim at a simultaneous description of the four channels $\gamma p \rightarrow n\pi^+$, $\gamma p \rightarrow p\pi^0$, $\gamma n \rightarrow p\pi^-$ and $\gamma n \rightarrow n\pi^0$. The dominant exchanges in this model are, for forward charged pion photoproduction the π and ρ trajectories, for forward neutral pion photoproduction the ρ and ω trajectories, and for backward pion photoproduction the N and Δ trajectories. In this Letter we will concentrate on the charged pion photoproduction reactions for which the expressions for the π and ρ Regge propagators are :

$$\mathcal{P}_{Regge}^\pi = \left(\frac{s}{s_0}\right)^{\alpha_\pi(t)} \frac{\pi\alpha'_\pi}{\sin(\pi\alpha_\pi(t))} \frac{\mathcal{S}_\pi + e^{-i\pi\alpha_\pi(t)}}{2} \frac{1}{\Gamma(1+\alpha_\pi(t))}, \quad (1)$$

$$\mathcal{P}_{Regge}^\rho = \left(\frac{s}{s_0}\right)^{\alpha_\rho(t)-1} \frac{\pi\alpha'_\rho}{\sin(\pi\alpha_\rho(t))} \frac{\mathcal{S}_\rho + e^{-i\pi\alpha_\rho(t)}}{2} \frac{1}{\Gamma(\alpha_\rho(t))}, \quad (2)$$

where s_0 is a mass scale which is conventionally taken as $s_0 = 1 GeV^2$ [2] and $S = \pm 1$ is the signature of the trajectory. The π and ρ Regge trajectories are given by $\alpha_\pi(t) = \alpha'_\pi * (t - m_\pi^2)$ with $\alpha'_\pi = .7 GeV^2$ and $\alpha_\rho(t) = .55 + \alpha'_\rho * t$ with $\alpha'_\rho = .8 GeV^2$ (t in GeV^2). In this work the π and ρ trajectories are taken to be degenerate with the b_1 and a_2 trajectories respectively. This is done by adding (or subtracting) the non-degenerate trajectories of Eq.1 with the two opposite signatures (and similarly for the ρ trajectory of Eq.2) as is well known from Regge theory [2]. This leads to degenerate trajectories which have either a rotating ($e^{-i\pi\alpha(t)}$) or a constant (1) phase. For several charge and hypercharge exchange hadronic reactions these two possibilities (known as line-reversal symmetry) are well studied [7]. For the line-reversal-related processes $\gamma p \rightarrow n\pi^+$ and $\gamma n \rightarrow p\pi^-$, a description in terms of degenerate trajectories, leads to exchanges with a rotating phase for the π^+ channel and to exchanges with a constant phase for the π^- channel due to the alternating G -parity of the successive particles on the trajectory. The Regge propagators of Eqs.1 and 2 have the property that they reduce to the Feynman propagator $\frac{1}{t-m^2}$ if one approaches the first pole on the trajectory (i.e. $t \rightarrow m^2$). The expressions for the other Regge propagators and results for the other channels can be found in Ref.[5] and will be shown in a forthcoming article [6].

The t -channel π diagram and u -channel nucleon diagram alone do not satisfy

electromagnetic gauge invariance by themselves. The exchange of a single pion in the t -channel e.g. has to be complemented with a s -channel nucleon exchange diagram (in the case of the $\gamma p \rightarrow n \pi^+$ reaction) to satisfy gauge invariance, as is well known for Born diagrams. If one reggeizes the π -exchange as in Eq.1, the gauge invariance has to be implemented by reggeizing the s -channel nucleon diagram (where one considers only a pointlike $\gamma.V.N$ coupling) in the same way as the t -channel π diagram. This is done here by multiplying the s -channel nucleon diagram by $\mathcal{P}_{Regge}^\pi \cdot (t - m_\pi^2)$. This implementation of gauge invariance insures that one recovers the result obtained for the Born diagrams if one is close to the pion pole ($t \rightarrow m_\pi^2$), as $\mathcal{P}_{Regge}^\pi \cdot (t - m_\pi^2) \rightarrow 1$ for $t \rightarrow m_\pi^2$. This implementation of gauge invariance is one new feature of the present model compared to various previous works and turns out to be crucial to obtain a good description of polarization observables and to describe the ratio of π^-/π^+ photoproduction as will be shown further on.

The pion photoproduction amplitudes are obtained by using the same electromagnetic and hadronic vertices as in Ref.[4] where the corresponding expressions can be found. In Ref.[4], all coupling constants are well established through the precise studies and analyses of the numerous pion photoproduction data in the Δ -resonance region. Contrary to other Regge analyses of the pion photoproduction reaction (e.g. see Ref.[8] for a recent analysis), the coupling constants in the present model are not treated as fit parameters but are determined from the studies in the resonance region.

The resulting model which is simple (in terms of the number of trajectories that are exchanged), economical (in terms of number of parameters) and most importantly consistent (with studies in the resonance region for the determination of these parameters), gives a reasonable and coherent description of all the existing data of pion photoproduction at forward and backward angles (differential cross-sections as well as single polarization observables) for photon energies $E_\gamma \gtrsim 4 \text{ GeV}$. Figs. 1-3 show some results of our model.

In Fig.1, the forward differential cross section for charged pion photoproduction clearly shows a sharp rise (over a range $\Delta t \approx m_\pi^2$) at very forward angles. As the contribution of the t -channel π diagram alone goes to zero for $t \rightarrow 0$, the sharp rise of the cross section naturally follows in the present model from the implementation of gauge invariance. This feature was also found within the context of the Electric Born Term Model [9][10] (where one implements only Born diagrams), which however cannot explain the energy and exponential t -dependence of the differential cross section. Traditionally, Regge analyses explained this forward peak in pion exchange reactions (both by electromagnetic and hadronic probes) as being due to absorption corrections [7]. These absorption models rely on the fit of a free parameter and lead to an unphysical sign reversal of the lowest partial waves if one fits the charged pion photoproduction data. Moreover, these absorption models do not respect gauge invariance which is a fundamental constraint for electromagnetic induced reactions.

The implementation of gauge invariance is also crucial in the description of the charged pion photon asymmetry data as is seen from Fig.2. As is well known

Fig. 1. Differential cross section $\frac{d\sigma}{dt}$ for the $\gamma p \rightarrow n\pi^+$ reaction for different photon (lab) energies : $E_\gamma = 5, 8, 11, 16$ GeV. The references to the data can be found in the compilation given in Ref.[8].

[9], unnatural parity exchange (like π -exchange) will lead to an asymmetry of -1 at low $-t$, whereas natural parity exchange (like ρ -exchange) will lead to an asymmetry of +1 at low $-t$. The experimental data for the photon asymmetry at high energies (Fig.2) also show a rapid rise at low $-t$ ($\Delta t \approx m_\pi^2$). This is again naturally explained in the present model by the reggeized s -channel nucleon diagram, which guarantees the gauge invariance of the model. At larger values of $-t$ the asymmetry rises to +1, which points to the dominance of the ρ -exchange, as can also be seen from the differential cross section in Fig.1.

The present model also describes at the same time the existing data for the $\gamma n \rightarrow p\pi^-$ reaction as is shown in Fig.3 where the ratio of π^-/π^+ differential cross section is plotted. This observable was found to be difficult to describe in various Regge absorption models [11]. It is completely constrained once one has a model for $\gamma p \rightarrow n\pi^+$, as the two reactions are related by isospin and line-reversal. For the implementation of gauge invariance, the π -exchange diagram is complemented by a reggeized s -channel nucleon pole diagram for $\gamma p \rightarrow n\pi^+$ and by a reggeized u -channel nucleon pole diagram for $\gamma n \rightarrow p\pi^-$. The good description of this ratio in the present model follows from both the use of degenerate trajectories with line-reversal symmetry and the implementation of gauge invariance : this is a new feature of this model compared to previous works.

Although we only show the results for charged pion photoproduction in this Letter, the present model also gives a satisfactory description of the neutral

Fig. 2. Photon asymmetry for the reaction $\gamma p \rightarrow n\pi^+$. The references to the data can be found in the compilation given in Ref.[8].

pion photoproduction channels. Furthermore, we also extended [5] the present model to the $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions. These results will be shown in a forthcoming article [6].

Having obtained a good description of pion photoproduction observables at high energy and low momentum transfer, the question can be raised how to extend this model to larger momentum transfer. When extrapolated towards the high p_T region (large $-t$ and large $-u$), a model based on linear Regge trajectories falls short to reproduce the data. One approaches the “hard” process region where the experimental data exhibit a different behavior. At scattering angles close to 90° in the center of mass frame, the differential cross-section is more or less independent of t (plateau) and scales as s^{-7} with energy. This latter behavior is simply and naturally explained by the counting rules [12] which interpret the large p_T reactions as simple scatterings of partons. Clearly, we enter the domain of pQCD which in principle allows us to calculate and quantify exactly these interactions. The question can be raised however down to which transfer one can still apply pQCD? There is therefore a clear interest for a complementary approach which would link, extrapolate between the low and high momentum transfer regions.

To construct the amplitude $\mathcal{M}_{hard}$ at high momentum transfer, we apply a prescription inspired from Ref.[13] to the pion photoproduction reaction. In

Fig. 3. Ratio R of differential cross sections : $\frac{d\sigma(\gamma n \rightarrow \pi^- p)}{dt} / \frac{d\sigma(\gamma p \rightarrow \pi^+ n)}{dt}$. The references to the data can be found in the compilation given in Ref.[8].

Ref.[13], the factorization formula was proposed

$$\mathcal{M}_{hard} = \mathcal{M}_{soft} \times F_3(t) \times F_4(t) , \quad (3)$$

where $\mathcal{M}_{soft}$ is the amplitude of our Regge exchange model and $F_3(t)$ and $F_4(t)$ are the form factors of the two outgoing particles of the considered exclusive reaction ($12 \rightarrow 34$). One of the ways to reconcile at higher momentum transfer, the Regge exchange model with experiment and the counting rules is to assume that the Regge trajectories saturate at -1 for $t \rightarrow -\infty$, as was shown in Ref.[13] for the case of nucleon-nucleon and pion-nucleon scattering. For meson trajectories this result was shown [14] to follow from a QCD motivated effective interquark potential of the form :

$$\mathcal{V}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + \kappa r + \mathcal{V}_0 . \quad (4)$$

where the first term represents the short distance part of the quark-antiquark interaction and corresponds to one gluon exchange, whereas the term which is linear in r , leads to confinement (κ is known as the “string tension”).

The eigenvalue equation ($E^2 = t$ as function of the angular momentum α)

Fig. 4. Saturation of the π and ρ trajectories.

of the potential of Eq.4 was inverted in Ref.[14] and the resulting equation for α was analytically continued into the scattering region ($t < 0$). This leads to the interpolating π and ρ Regge trajectories shown in Fig.4. As one observes, they become linear as $t \rightarrow \infty$ which reflects the bound state spectrum and saturate at -1 for $t \rightarrow -\infty$ which reflects the hard scattering (pQCD) region. The resulting hard scattering amplitude of Eq.3 with these saturating trajectories, has a t -dependence which is much flatter than the exponential t -dependence of the “soft” model. This leads to a plateau for the differential cross section at large p_T . Moreover the differential cross section will satisfy the counting rules as shown in Ref.[13] because of the saturating trajectories and because of the form factors of the outgoing particles. Let us also remark that the high momentum transfer amplitude of Eq.3 is normalized by the low momentum transfer amplitude.

We present on Fig. 5 the result of this prescription for the reaction $\gamma p \rightarrow n\pi^+$ at the two photon energies $E_\gamma = 5\text{GeV}$ and $E_\gamma = 7.5\text{GeV}$ for which data exist at high momentum transfer. Firstly, we show on the figure the “soft” model with linear trajectories in the t -channel (meson exchanges) and in the u -channel (baryon exchanges). In the u -channel, the model follows the same lines as in the t -channel and is documented in Ref.[5][6]. We clearly see that the extrapolation to large p_T of the model with linear trajectories cannot reproduce the plateau appearing around $|t| \approx 2.5\text{GeV}^2$ in the differential cross section. The disagreement increases as the incident photon energy rises. On the other hand, the “hard” model which is obtained by extrapolating the forward amplitude to high p_T by saturating the trajectories and by using form factors for the outgoing particles (for the nucleon form factor F_4 in Eq.3, the electric

Fig. 5. Extension at large p_T for $\frac{d\sigma}{dt}(\gamma p \rightarrow n\pi^+)$. Solid lines : “soft” model. Dashed lines : “hard” model. The references to the data at low t and low u can be found in the compilation given in Ref.[8], whereas the high p_T data are from Ref.[15].

form factor was taken, whereas the unknown transition form factor F_3 was set to be 1), reproduces relatively well the shape, the energy dependence and the magnitude of the large p_T plateau.

At backward angles, the data, similarly as for the forward region, show a flattening of the differential cross section as one approaches the high p_T region. A difference is however that the change of slope occurs at smaller $-u$ values (compared to $-t$ values), which could be a hint that one approaches the “hard” mechanism earlier in the backward region. One can also try to extrapolate the amplitude to the high p_T region by saturating baryon trajectories in the u -channel as the slopes of meson and baryon Regge trajectories are similar. Although theoretically less founded (the 2-quark potential of Eq.4 should not be so simply adapted for baryons), we have explored this approach and display the results of the backward extrapolation on Fig. 5 as well. The two extrapolations constitute thus two limits of the same amplitude and provide alternative approaches to the hard scattering regions. Again, the rare data at backward angles imposing few constraints on the low- u model and the approximation of a two-body potential for the baryons to larger $-u$ makes this latter “ u -side” extrapolation more uncertain. Although both produce a plateau at large angle, these less well-founded hypotheses can be responsible for the quantitative

difference in the “overlap” central region.

Fig. 6. Extension at large p_T of the model for the target asymmetry of $\gamma p \rightarrow n\pi^+$. The references to the data can be found in the compilation given in Ref.[8].

We also present on Fig. 6 the extrapolation at large $-t$ for the target asymmetries for the reaction $\gamma p \rightarrow n\pi^+$. The extrapolation of the soft and of the hard model are to be compared with the predictions of pQCD which give a zero asymmetry because of Hadron Helicity Conservation [16]. It is clear that polarization observables are a very sensitive tool to study this transition domain, from partonic to hadronic degrees of freedom, from pQCD to effective hadronic models.

We have presented in this Letter a Regge-based model for low momentum transfer reactions. For the pion photoproduction reaction, data are relatively numerous and permit to calibrate a consistent and reliable model which is gauge invariant and whose parameters are well determined by the precise studies and analyses in the resonance region. The implementation of gauge invariance and the use of degenerate trajectories are a new feature of the present model which is responsible for the good description of polarization observables and the π^-/π^+ ratio. We have been looking to extrapolate our model to the large p_T domain. This was done by introducing two additional notions : the

saturation of Regge trajectories and the introduction of form factors. The resulting “hard” model describes reasonably well the main features of the (rare) large p_T experimental data. From a practical point of view, we have here a tool which allows to describe high momentum transfer reactions economically. With the emergence of the new high energy, high duty-cycle accelerators, these largely unexplored kinematical regions will become accessible experimentally. In this respect, the model which we presented here can constitute a realistic event generator for the estimation of counting rates, background and studies of experiment feasibility. More fundamentally, we have here an approach alternative to pQCD in the transition region between soft and hard processes which is a step towards a more profound understanding of non-perturbative QCD.

The authors would like to thank G.Cohen-Tannoudji, E. Predazzi and B. Saghai for useful discussions and critical remarks. This work was supported in part by the EU/TMR contract ERB FMRX-CT96-0008.

References

- [1] J. Arvieux and B. Pire, *Prog.Part.Nucl.Phys.* **35** (1995) 299.
- [2] P.D.B. Collins, “*An introduction to Regge theory and high energy physics*”. Cambridge University Press, Cambridge, 1977.
- [3] J.K. Storrow, *Rep.Prog.Phys.* **50** (1987) 1229.
- [4] M. Vanderhaeghen, K. Heyde, J. Ryckebusch and M. Waroquier, *Nucl.Phys.* **A595** (1995) 219.
- [5] M. Guidal, PhD thesis, DAPNIA/SPhN-96-03T, CE Saclay. 1996, unpublished.
- [6] M. Guidal, J.M. Laget and M. Vanderhaeghen, article in preparation.
- [7] A.C. Irving and R.P. Worden, *Phys.Rep.* **34** (1977) 117.
- [8] M. Rahnema and J.K. Storrow, *J.Phys.G: Nucl.Part.Phys.* **17** (1991) 243.
- [9] J.K. Storrow, in *Electromagnetic Interactions of Hadrons*, Vol.1, Eds. A. Donnachie and G. Shaw. Plenum Press, New York, 1978.
- [10] L.M. Jones, *Rev.Mod.Phys.* **52** (1980) 545.
- [11] R. Worden, *Nucl.Phys.* **B37** (1972) 253.
- [12] S.J. Brodsky and G.R. Farrar, *Phys.Rev.Lett.* **31** (1973) 1153.
- [13] P.D.B. Collins and P.J. Kearney, *Z.Phys.* **C22** (1984) 277.
- [14] M.N. Sergeenko, *Z.Phys.* **C64** (1994) 315.
- [15] R.L. Anderson et al., *Phys.Rev.D* **14** (1976) 679.
- [16] S.J. Brodsky and G.P. Lepage, *Phys.Rev.D* **24** (1981) 2848.